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Accelerated Stress Testing of Thin-Film Modules with SnO_2:F Transparent Conductors

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ABSTRACT

This paper reviews a testing program conducted at NREL for the past two years that applied voltage, water vapor, and light stresses to thin-film photovoltaic (PV) modules with SnO_2:F transparent conducting oxides (TCOs) deposited on soda-lime glass superstrates. Electrochemical corrosion at the glass-TCO interface was observed to result in delamination of the thin-film layers. Experimental testing was directed toward accelerating the corrosion and understanding the nature of the resulting damage.

1. Introduction

Corrosion and delamination of tin oxide TCO layers from glass superstrates in a-Si PV modules has been reported in the literature [1,2,3]. Solarex (now BP Solar) reported such damage in two small grid-connected PV systems with operating voltages of about 200 Vdc [1], and the Jet Propulsion Laboratory (JPL) was able to reproduce the effect in laboratory conditions using an accelerated damp heat with voltage bias test [2]. BP Solar recommended using the JPL test in module qualification sequences [3]. In 2000 we began a program using the JPL test to study the susceptibility of modern thin-film modules to this effect; much of this work is the subject of a paper currently in press [4]. This paper reviews this work, but includes some newer results that were not available when the journal article was prepared. Finally, Energy Photovoltaics (EPV) has recently developed a simple test for TCO corrosion that can be performed on glass coupons coated with tin oxide, thereby eliminating the need to test an entire module [5].

Thin-film, glass-superstrate PV modules differ from conventional crystalline-Si modules in that they lack the additional isolation from the outside environment afforded by the ethylene vinyl acetate (EVA) encapsulant between the Si solar cells and the top glass sheet. This difference is important because leakage currents through the glass or the module edges can easily reach the active semiconductor layers.

2. Accelerated Testing

The first experiment we performed placed two identical a-Si modules into an environmental chamber set for an ambient temperature of 85°C and a relative humidity (RH) of 85% (these are the standard damp heat conditions). With the output leads of the modules shorted, +600 V relative to the aluminum frame around the outside edges was applied to one module and –600 V to the other module. Leakage currents were monitored during the exposure. Several hundred hours at this condition produced almost no visible results in the +600 V polarity, while the opposite polarity caused a large amount of so-called "bar graphing," as seen in Fig. 1. These visual effects are actually cracks in the TCO that extend through all of the semiconductor layers and the rear metallization.

The strong dependence on the bias polarity suggests that the damage is associated with the electric field direction and mobile ions, especially Na^+. Solarex verified that sodium is required for the damage by fabricating modules on borosilicate superstrates rather than soda-lime glass, and did not observe any corrosion following biased damp heat testing [6].

3. Temperature Dependence

We next attempted to measure the temperature dependence of the effect, although quantification of the damage was not a simple matter. Loss of performance might be selected as an indicator, but performance is affected by a large number of factors, and it is difficult to remove the effects of the damp heat testing from those of the electrochemical corrosion. Because the damage is easily visible, we chose instead to measure the damage area.

Three a-Si modules were subjected to biased damp heat in succession with varying chamber temperatures of 85°, 72°, and 60°C. At periodic intervals, the modules were removed from the chamber and the damage area measured. These results are presented in Fig. 2, from which we obtained an activation energy of 0.78 eV [4]. Typical activation energies for the electrical conductivity of soda-lime glass are in the 0.80–0.82-eV range, and our value compares closely to the one reported by EPV, 0.79 eV [5].

4. CdTe Testing

In an attempt to determine if thin film modules other than a-Si can exhibit similar TCO corrosion, a CdTe module was placed in 85°C and 85% RH at –600 V. Because this module lacked a metallic frame, the bias voltage was applied between the shorted leads and the mounting lugs glued to the rear glass provided by the manufacturer. No damage was visible after more than 500 h of exposure. The negative result could be explained in two ways: (1) the corrosion process requires a-Si, or (2) the lack of a frame prevented any damage.

To answer this question, a frame was removed from an a-Si module and installed on a CdTe one; both modules were then subjected to 1200 h of biased damp heat at the same time. The leakage currents in the a-Si module were reduced by nearly two orders of magnitude, and TCO corrosion developed in the CdTe module. We were therefore led to conclude that the corrosion depends only on the glass superstrate and the TCO layer, and not on any semiconductor absorber materials.

6. Analysis of Damage

At this point, it seemed desirable to examine the damage as closely as possible to help understand what is happening to the TCO layers. Core samples were cut from modules exposed to biased damp heat, in both damaged and undamaged areas. Figure 3 shows two of these core samples. In undamaged areas (Fig. 3 bottom), the TCO adhesion is still very high, and it is quite difficult to separate the top and bottom glasses. On the other hand, there is almost zero adhesion of the tin oxide to the glass superstrate in completely damaged regions (Fig. 3 top). Figure 4 is a 50× micrograph of the superstrate of the top core sample in Fig. 3, and shows that no TCO remains on the glass surface *except* near the TCO laser scribe lines. Apparently, the TCO laser ablation process modifies the TCO adjacent to the scribe line in a way that prevents electrochemical corrosion.

Optical micrographs of partly damaged regions through the top glass superstrate also yielded some interesting results. These are areas where the cracking has begun, but has not yet progressed to complete delamination. An example of such a region is visible in Fig. 1 where the long tendrils seem to extend out from the highly crazed whitish areas. When a partly damaged region was examined with optical microscopy, the cracks are seen, but in areas away from the cracks, interference fringes are visible (Fig. 5). This seems to indicate that the delamination process involves more than just the cracking.

7. New Accelerated Testing

During discussions of the tin oxide problem, BP Solar suggested using the facilities available at NREL to verify the validity of the biased damp heat test [7]. Because there is no light on the test modules, it can be argued the test is an artificial one that produces stresses that will not occur in actual use. However, a-Si modules installed outdoors in PV systems do show TCO corrosion, as illustrated in Fig. 6, although without the extreme bar graphing. This module operates at about 60 V, which results in an internal electric field between the two white electrical bus (frit) lines.

Using our Atlas XR-260 environmental chamber that features four 1-kW Xe arc lamps, we began a test to see if similar damage can be replicated indoors. A resistive load was placed across the module leads, and the chamber controls were set to give 1-sun irradiance at 85% RH and 48°C. Note that this lower ambient temperature was needed to obtain a module temperature of 85°C under illumination. After 500 h, similar damage was observed, as seen in Fig. 7 (this module had a different laser scribing pattern). The polar nature of the corrosion is clearly evident in this image.

This simple test should be valid for a system consisting of just a single module, but larger systems can have series module strings with voltages up to 600 V between the leads and the grounding points. To simulate this, the same illuminated damp heat test was performed, but with –600 V applied between the frame and the resistor lead connected to the positive module lead. After nearly 2000 h of exposure, the corrosion around the exit leads was again seen, plus bar graphing at the opposite end of the module that progressed very slowly (see Fig. 8).

Consideration of why the corrosion might progress at a rate so much slower than the dark test led us to consider a crucial difference — the ambient temperature inside the test chamber, which had to be reduced to 48°C to obtain a *module* temperature of 85°C under illumination. Because of this, the amount of water vapor inside the chamber is actually much less, plus the fact that the module itself is at a much higher temperature means that very little water vapor can condense on the module surfaces. Thus, the damaging leakage currents are reduced [4].

We then wondered if a further modification to the test might overcome the lack of acceleration. During daily operation, it is common for modules to be wet from dew in the early morning, but how can this be simulated? This same issue is encountered in the materials-weathering industry, which has developed light-dark cycling as a solution (periodic water-spray cycles are also used). In fact, such cycling has been found to be much more stressful than either light or dark exposure alone. This is because the dark cycles can force water vapor into the test sample, which is then followed by the stress of sunlight.

Therefore, the following test was devised. Identical conditions were used for a 2-h light cycle, i.e., 48°C ambient temperature, 85% RH, 1-sun. Following this cycle, the illumination was turned off and the ambient temperature raised to 85°C for 2 h. The –600 V bias was applied during both cycles. The damage area was measured, and the results are plotted in Fig. 8 (note that in Fig. 8 the number of cycles completed has been converted to time). Visually, the damage to module #9109 was very similar to that of module #5475 (light-only), but the bar graph corrosion progressed at a rate about 30 times faster, although the corrosion rate is not linear.

8. Conclusions

As a result of this study, we have made a number of conclusions concerning the electrochemical corrosion and delamination of SnO_2:F on soda-lime glass:

(1) The corrosion depends on the direction of the internal electric fields.

(2) Corrosion causes cracking that extends through all of the thin-film PV layers.

(3) Water vapor enhances the corrosion by increasing the conductivity of the front glass surface.

(4) Metallic module frames can greatly enhance the damage process.

(5) Damage has been found to occur in both a-Si and CdTe modules.

(6) A 0.78-eV thermal activation energy of the damage area versus time at 85% RH was found.

(7) The biased damp heat test with illumination causes damage identical to that observed in actual use.

(8) Damage rates can be dramatically increased by using light/dark cycles with biased damp heat.

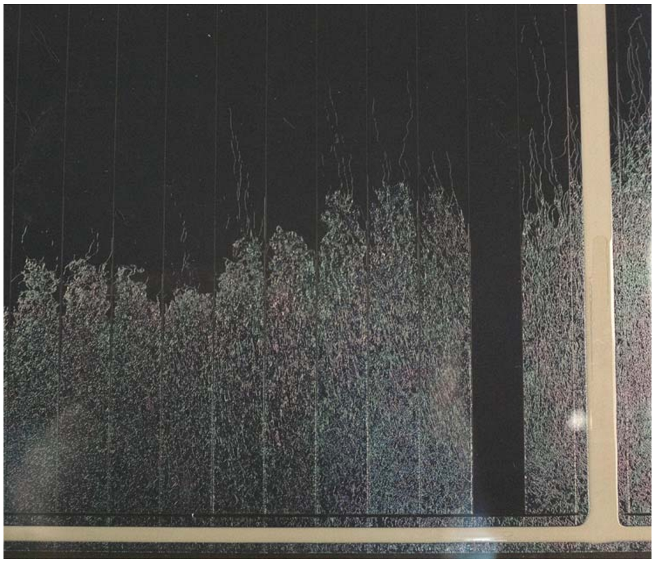

Figure 1. Front surface of a-Si module after 200 h at 85°C, 85% RH, and –600 V bias.

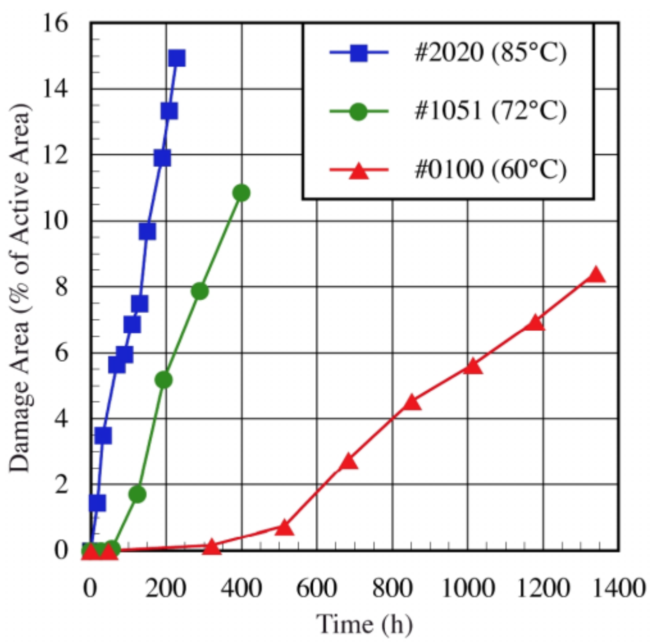

Figure 2. Active module area damaged by –600 V biased damp heat exposure as a function of time.

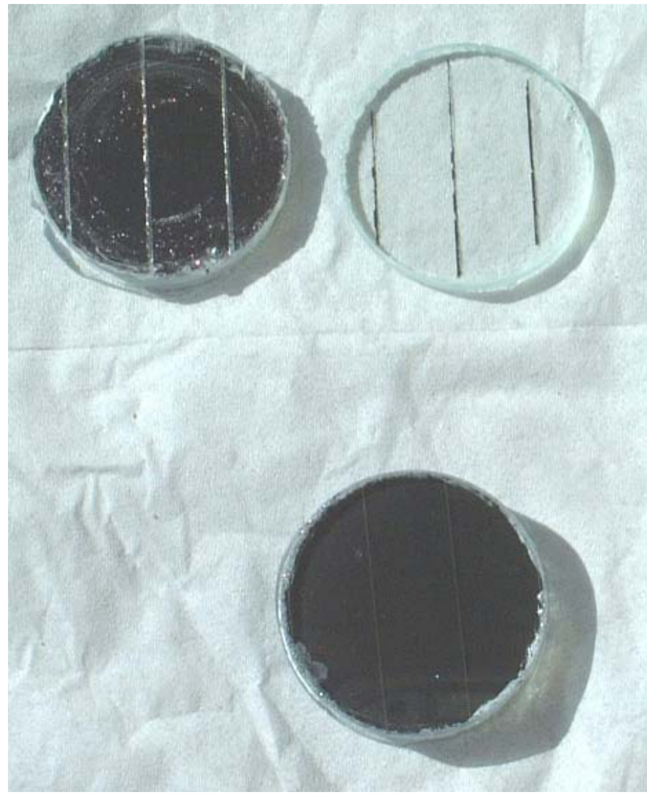

Figure 3. Two cored sections 25 mm in diameter from an a-Si module subjected to biased damp heat. This module design was a glass superstrate laminated with EVA to a glass backsheet. The bottom core was from a location that did not have visible damage, whereas the top core was from a region of total delamination of the SnO_2 from the top glass. Thus, the top right section is the superstrate glass, whereas the top left section is the backsheet with all the thin film layers adhering to the EVA.

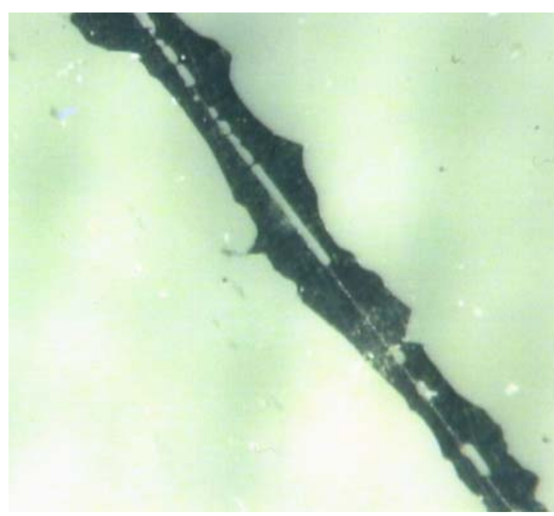

Figure 4. A 50× optical micrograph of the top glass superstrate shown in Fig. 5, along one of the TCO laser scribe lines. Away from the scribe line, no TCO remains on the glass surface.

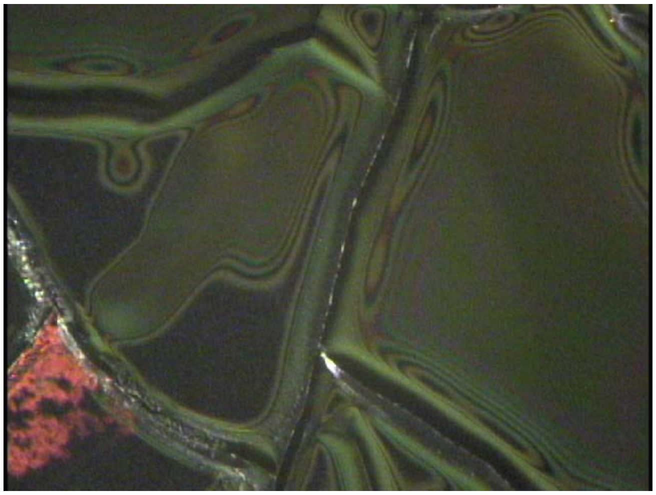

Figure 5. A 100× optical micrograph through the top glass of an a-Si module in an area only partly damaged by the TCO corrosion.

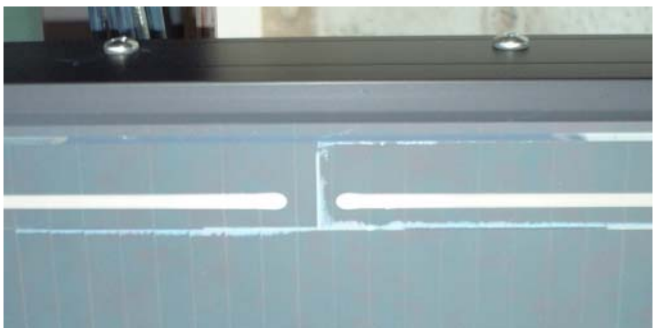

Figure 6. A photograph of the front surface of an a-Si module installed in a 1-kW PV system at NREL for about 3 years.

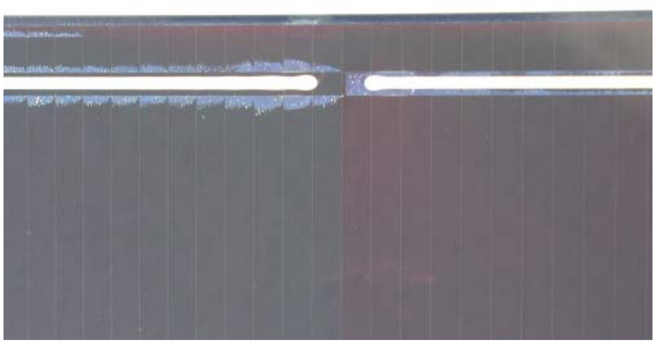

Figure 7. TCO corrosion in an a-Si module after 500 h of exposure to 1-sun, 85% RH, and 85°C module temperature.

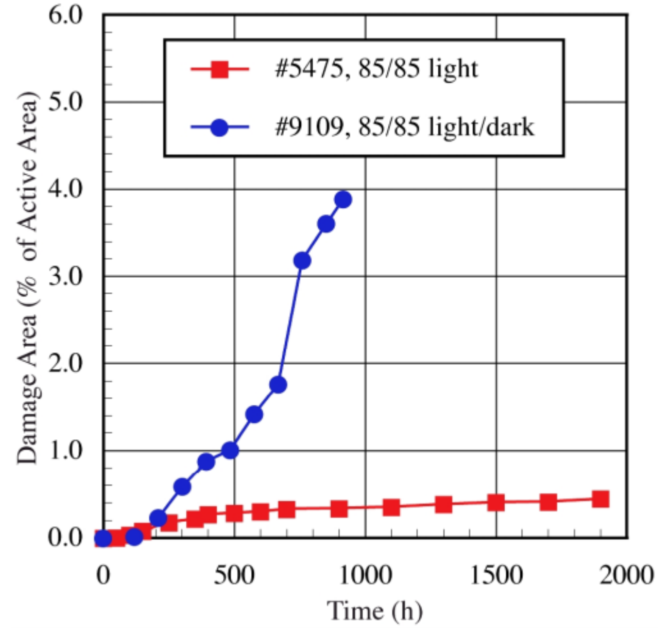

Figure 8. TCO damage area as a function of exposure time in an illuminated damp heat environment (see text).

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REFERENCES

[1] D.A, Fagnan, R.V. D'Aiello, and J. Mongon. "Solarex/Philadelphia Electric amorphous silicon PV test site," *Proc. of the 19th IEEE PV Specialists Conference, 1987, New Orleans, LA,* pp. 1508–1509.

[2] G. Mon, L. Wen, J. Meyer, R. Ross, Jr., A. Nelson. "Electrochemical and galvanic corrosion effects in thin-film photovoltaic modules," *Proc. of the 20th IEEE PV Specialists Conference, 1987, Las Vegas, NV,* pp. 108–113.

[3] J.H. Wohlgemuth, M. Conway, and D.H. Meakin. "Reliability and performance testing of photovoltaic modules," *Proc. of the 28th IEEE PV Specialists Conference, 2000, Anchorage, AK,* pp. 1483–1486.

[4] C.R. Osterwald, T.J. McMahon, and J.A. del Cueto. "Electrochemical corrosion of SnO_2:F transparent conducting layers in thin film photovoltaic modules," *Sol. Eng. Mat. and Sol. Cells,* in press, 2003.

[5] K.W. Jansen and A.E. Delahoy. "A laboratory technique for the evaluation of electrochemical transparent conductive oxide delamination from glass substrates," *Thin Solid Films* **423** (2003) pp. 153–160.

[6] D.E. Carlson, private communication, 2001.

[7] J.H. Wohlgemuth, private communication, 2002.

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